Chapter 6

APPLICATIONS: NANODEVICES, NANOELECTRONICS, AND NANOSENSORS

Contact Persons: J. Jasinski, IBM; P. Petroff, University of California, Santa Barbara

6.1 VISION

In the broadest sense, nanodevices are the critical enablers that will allow mankind to exploit the ultimate technological capabilities of electronic, magnetic, mechanical, and biological systems. While the best examples of nanodevices at present are clearly associated with the information technology industry, the potential for such devices is much broader. Nanodevices will ultimately have an enormous impact on our ability to enhance energy conversion, control pollution, produce food, and improve human health and longevity.

6.2 CURRENT SCIENTIFIC AND TECHNOLOGICAL ADVANCEMENTS

Current Scientific Advances

In the past decade, our ability to manipulate matter from the top down, combined with advances and in some cases unexpected discoveries in the synthesis and assembly of nanometer-scale structures, has resulted in advances in a number of areas. Particularly striking examples include the following:

- The unexpected discovery and subsequently more controlled preparation of carbon nanotubes and the use of proximal probe and lithographic schemes to fabricate individual electronic devices from these materials (Iijimi 1991; Guo et al. 1995; Tans et al. 1997; Bockrath et al. 1997; Collins et al. 1997; Martel et al. 1998)
- The ability in only the last one or two years to begin to place carefully engineered individual molecules onto appropriate electrical contacts and measure transport through the molecules (Bumm et al. 1996; Reed et al. 1997)
- The explosion in the availability of proximal probe techniques and their use to manipulate matter and thereby fabricate nanostructures (Stroscio and Eigler 1991; Lyo and Avouris 1991; Jung et al. 1996; Cuberes et al. 1996; Resch et al. 1998)
- The development of chemical synthetic methods to prepare nanocrystals, and methods to further assemble these nanocrystals into a variety of larger organized structures (Murray et al. 1995)
- The introduction of biomolecules and supermolecular structures into the field of nanodevices (Mao et al. 1999)
- The isolation of biological motors, and their incorporation into nonbiological environments (Noji et al. 1997; Spudich et al. 1994)

Current Technological Advances

A number of examples of devices in the microelectronics and telecommunications industries rely on nanometer-scale phenomena for their operation. These devices are, in a sense, “one-dimensional” nanotechnologies, because they are micrometer-scale objects that have thin film layers with thicknesses in the nanometer range. These kinds of systems are widely referred to in the physics and electronics literature as two-dimensional systems, because they have two classical or “normal” dimensions and one quantum or nanoscale dimension. In this scheme, nanowires are referred to as one-dimensional objects and quantum dots as zero-dimensional. In this document, and at the risk of introducing some confusion, we have chosen to categorize nanodevices by their main feature nanodimensions rather than by their large-scale dimensions. Thus, two-dimensional systems such as two-dimensional electron gases and quantum wells in our notation are one-dimensional nanotechnologies, nanowires are two-dimensional nanotechnologies, and quantum dots are three-dimensional nanotechnologies. Examples include high electron mobility transistors, heterojunction bipolar transistors, resonant tunneling diodes, and quantum well optoelectronic devices such as lasers and detectors.

The most recent success story in this category is that of giant magnetoresistance (GMR) structures. These structures can act as extremely sensitive magnetic field sensors. GMR structures used for this purpose consist of layers of magnetic and nonmagnetic metal films. The critical layers in this structure have thicknesses in the nanometer range. The transport of spin-polarized electrons that occurs between the magnetic layers on the nanometer length scale is responsible for the ability of the structure to sense magnetic fields such as the magnetic bits stored on computer disks. GMR structures are currently revolutionizing the hard disk drive magnetic storage industry worth $30-40 billion/year (Prinz 1998; Disktrend 1998, Gurney and Grochowski 1998; Grochowski 1998). Our ability to control materials in one dimension to build nanometer-scale structures with atomic scale precision comes from a decade of basic and applied research on thin film growth, surfaces, and interfaces.

The extension from one nanodimension to two or three is not straightforward, but the payoffs can be enormous. Breakthroughs in attempting to produce three-dimensional nanodevices include the following:

- Demonstration of Coulomb blockade, quantum effect, and single electron memory and logic elements operating at room temperature (Guo et al. 1997; Leobandung et al. 1995; Matsumoto et al. 1996)
- Integration of scanning probe tips into sizeable arrays for lithographic and mechanical information storage applications (Lutwyche et al. 1998; Minne et al. 1996)
- Fabrication of photonic band-gap structures (Sievenpiper et al. 1998)
- Integration of nanoparticles into sensitive gas sensors (Dong et al. 1997)

6.3 GOALS FOR THE NEXT 5-10 YEARS: BARRIERS AND SOLUTIONS

In order to exploit nanometer-scale phenomena in devices, we must have a better understanding of the electronic, magnetic, and photonic interactions that occur on and are unique to this size scale. This will be achieved through experiment, theory, and modeling over the next decade. In addition, new methods to image and analyze devices and device components will be developed. These might include three-dimensional electron microscopies and improved atomic-scale spectroscopic techniques.

Over the same time period, we believe that it will become possible to integrate semiconductor, magnetic, and photonic nanodevices as well as molecular nanodevices into functional circuits and chips.

The techniques now being developed in biotechnology will merge with those from nanoelectronics and nanodevices. Nanodevices will have biological components. Biological systems will be probed, measured, and controlled efficiently with nanoelectronic devices and nanoprobes and sensors.

There will be significant progress in nanomechanical and nanobiomechanical systems, which will exhibit properties that are fundamentally different from their macroscopic counterparts.

There are important applications for instruments that will fly into space: nanocomponents are needed to achieve overall instrument sizes in the micron or millimeter range (http://www.ipt.arc.nasa.gov; http://www.cism.jpl.nasa.gov). Some of the same issues apply to battlefield sensors for situational awareness.

Finally, a significant goal is the development of nanometer-scale objects that manipulate and perform work on other nanometer-scale objects, efficiently and economically achieving the same things we currently rely on scanning tunneling microscopy (STM) or atomic force microscopy (AFM) to carry out. A first step towards this goal might be the integration of nanometer-scale control electronics onto micromachines.

Paradigm Shifts

In the information technology arena, nanodevices will both enable and require fundamentally new information processing architectures. Early examples of possible architectural paradigm shifts are quantum computation (Shor 1994; DiVincenzo 1995; Gershenfeld and Chuang 1997), quantum dot cellular automata (Lent and Tougaw 1997; Orlov et al. 1997), molecular electronics (Ellenbogen and Love 1999), and computation using DNA strands (Adleman 1994; Adleman 1998). Such architectures will fundamentally change the types of information technology problems that can be attacked. Effective implementation of these types of architecture will require nanodevices.

Other paradigm shifts include the emergence of quantized magnetic disks (Chou and Krauss 1996); single photonic systems (Kim et al. 1999) that will allow efficient optical communication; nanomechanical systems (Gimzewski et al. 1998); a broad class of structures and devices that merge biological and non-biological objects into interacting systems (Alivisatos et al. 1996; Mucic et al. 1998); and use of nanocomponents in the shrinking conventional circuit architectures (Ellenbogen and Love 1999).

Research on nanodevices using nanoscale wiring and molecular logic, as well as new principles for devices such as spin electronics, have made significant inroads in the past year or two.

6.4 SCIENTIFIC AND TECHNOLOGICAL INFRASTRUCTURE

The exploration and fabrication of nanodevices requires access to sophisticated and sometimes expensive tools. More and better access to such equipment as well as rapid prototyping facilities is needed. Of equal importance is the recognition that success in nanodevices will draw upon expertise from a broad range of traditional disciplines. Therefore, it is imperative that programs be established that facilitate and strengthen cross-fertilization among diverse disciplines and that allow rapid adoption of new methods across field boundaries.

6.5 R&D INVESTMENT AND IMPLEMENTATION STRATEGIES

Nanodevices are in some ways the most complicated nanotechnological systems. They require the understanding of fundamental phenomena, the synthesis of appropriate materials, the use of those materials to fabricate functioning devices, and the integration of these devices into working systems. For this reason, success will require a substantial funding level over a long period of time. There is strong sentiment for single investigator funding as well as for structured support of interdisciplinary teams.

6.6 CONCLUSIONS AND PRIORITIES

Priorities in Research and Development

- Development of new systems and architectures for given functions
- Study of interfaces and integration of nanostructures into devices and systems
- Multiscale, multiphenomena modeling and simulation of complex systems

Priorities in Modes of Support

- Establishment of consortia or centers of excellence for the research priorities identified above, by using vertical and multidisciplinary integration from basic research to prototype development
- Encouragement of system integration at the nanoscale in research and education

6.7 EXAMPLES OF CURRENT ACHIEVEMENTS AND PARADIGM SHIFTS

6.7.1 Organic Nanostructures: The Electrical Conductivity of a Single Molecule

Contact person: H. Goronkin, Motorola

By combining chemical self-assembly with a mechanical device that allows them to break a thin gold wire with nanometer scale control, researchers have succeeded in creating a "wire" consisting of a single molecule that can connect two gold leads (Figure 6.1). Using this structure, they have been able to begin to measure and study the electrical conductivity of a single molecule.

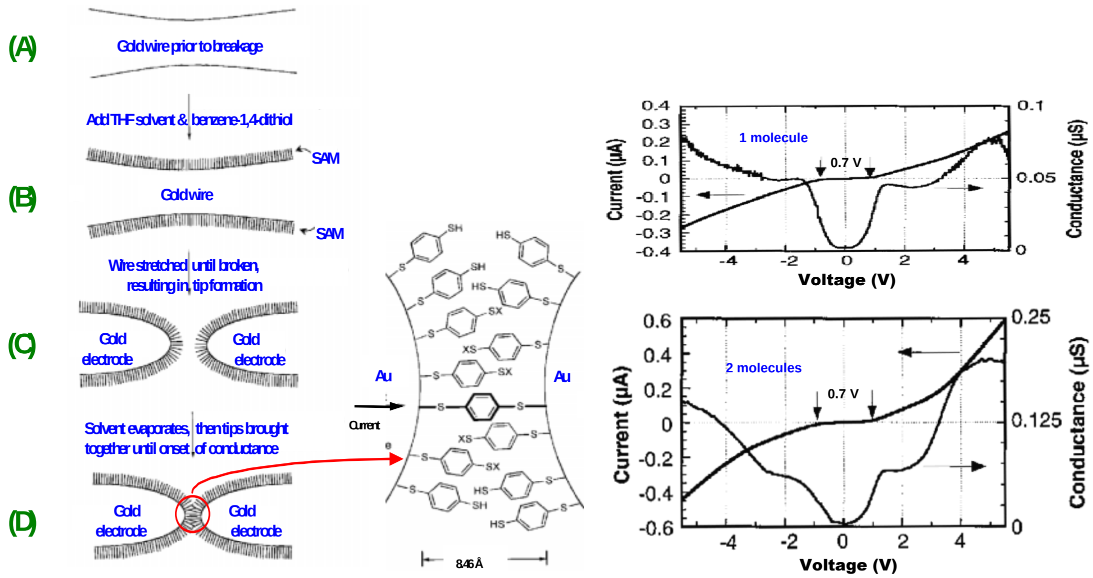

Figure 6.1. Organic nanostructures: on left, showing self-assembly of benzene-1,4-dithiol onto Au electrodes; on right, showing room-temperature I-V measurements suggesting presence of a Coulomb gap (reprinted with permission from Reed et al. 1997, ©1997 American Association for the Advancement of Science).

6.7.2 Molecular Electronics

Contact person: S. Williams, Hewlett-Packard

If the reduction in size of electronic devices continues at its present exponential pace, the size of entire devices will approach that of molecules within a few decades. However, well before this happens, both the physics upon which electronic devices are based and the manufacturing procedures used to produce them will have to change dramatically.

This is because current electronics are based primarily on classical mechanics, but at the scale of molecules, electrons are quantum mechanical objects. Also, the cost of building the factories for fabricating electronic devices, or fabs, is increasing at a rate that is much larger than the market for electronics; therefore, much less expensive manufacturing process will need to be invented.

Thus, an extremely important area of research is *molecular electronics*, for which molecules that are quantum electronic devices are designed and synthesized using the batch processes of chemistry and then assembled into useful circuits through the processes of self-organization and self-alignment. If molecular electronics achieves the ultimate goal of using individual molecules as switches and carbon nanotubes as the wires in circuits, we can anticipate nonvolatile memories with one million times the bit area density of today's DRAMs and power efficiency one billion times better than conventional CMOS circuitry. Such memories would be so large and power-efficient that they could change the way in which computation is performed from using processors to calculate on the fly to simply looking up the answer in huge tables.

A major limitation of any such process is that chemically fabricated and assembled systems will necessarily contain defective components and connections. This limitation was addressed in a 1998 paper entitled "A Defect-Tolerant Computer Architecture:

Opportunities for Nanotechnology" (Heath et al. 1998). By describing a silicon-based computer that was designed to operate perfectly in the presence of huge numbers of manufacturing defects, researchers from Hewlett-Packard (HP) and the University of California–Los Angeles (UCLA) presented an architectural solution to the problem of defects in molecular electronics, as described in Figure 6.2, and thus demonstrated in principle that manufacture by chemical assembly is feasible.

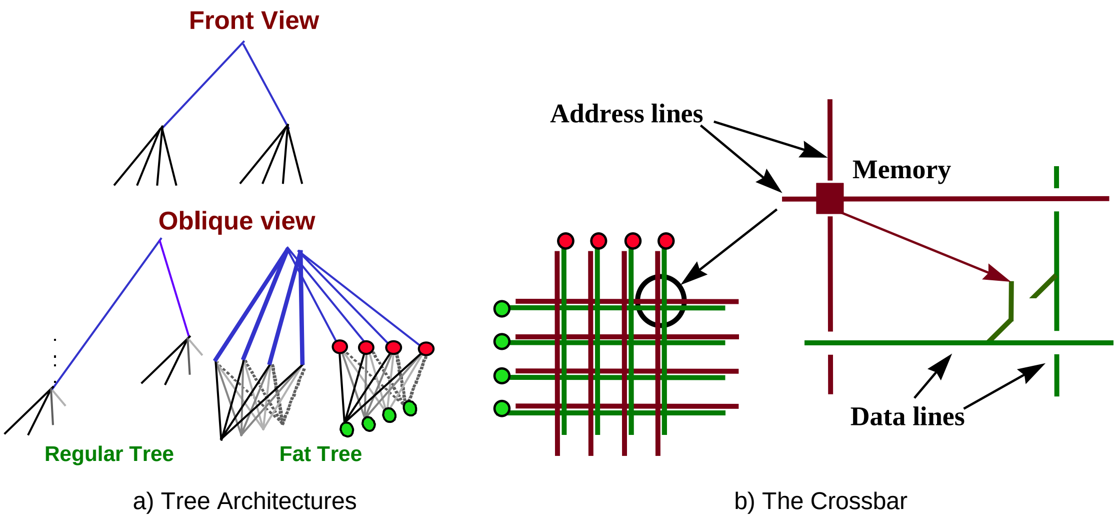

Figure 6.2. The logical design of a defect-tolerant circuit: (a) shows a "fat tree" architecture in which every member of a logical level of the tree hierarchy can communicate with every member at the next level; in the case of a defective component, this structure enables one to route around and avoid the defect; (b) shows how this architecture is implemented using cross bars, which are very regular structures and look like something that can be built chemically. The complexity required for a computer is programmed into the cross bars by setting the switches to connect certain elements of the tree together. Using silicon circuitry, two completely separate sets of wires (address and data lines) are required for the cross bars, and seven transistors are required for each switch, since a continual application of electrical power is required to hold the sense of the switches.

In 1999, researchers from HP Labs and UCLA experimentally demonstrated the most crucial aspect for such a system, an electronically addressable molecular switch that operates in a totally "dry" environment (Collier et al. 1999). As illustrated in Figure 6.3, logic gates were fabricated from an array of configurable molecular switches, each consisting of a monolayer of electrochemically active rotaxane molecules sandwiched between metal electrodes.

Figure 6.4 illustrates the operation of the switches. In the "closed" state, current flow is dominated by resonant tunneling through the electronic states of the molecules. The switches are irreversibly opened by applying an oxidizing voltage across the device. In this case, since the memory of the molecules is not volatile, only one set of wires is needed to set and read the state of the molecules, and in principle, one molecule can replace seven transistors in a conventional silicon circuit. In the demonstration, several devices were configured together to produce AND and OR logic gates. The high/low current levels of those gates were separated by factors of 15 and 30, respectively, which is a significant enhancement over that for conventional wired-logic gates.

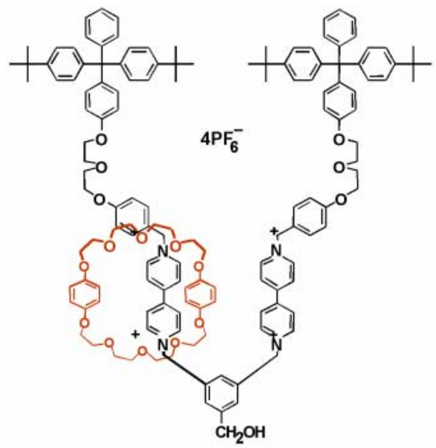

Figure 6.3. The atomic structure of one of the molecular switches used in the devices described above, which is known as a rotaxane (F. Stoddart, UCLA). This molecule conducts via resonant tunneling through unoccupied molecular orbitals when it is in its reduced chemical state (switch closed), but it is a tunneling barrier in its oxidized state (switch open). The switch can be closed electronically in a solid-state circuit by applying the appropriate voltage across the molecule (Balzani et al. 1998; Credi et al. 1997).

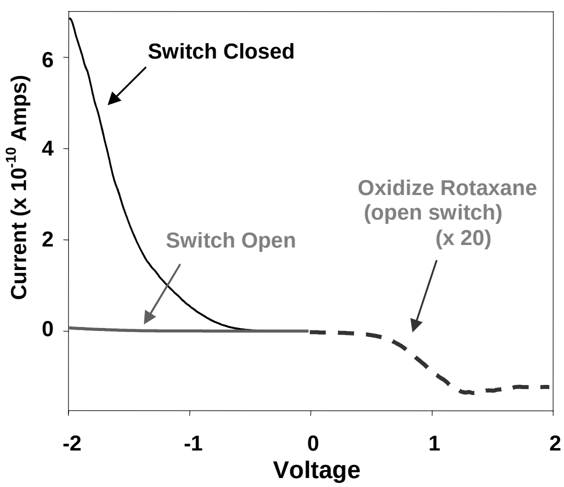

Figure 6.4. The current-voltage (I-V) characteristic of a large number of molecular switches is shown in both the "on" and "off" states. Initially, the molecular switches are closed, and applying a negative voltage across the molecules results in a "large" current flow that varies exponentially with the magnitude of the applied voltage. This portion of the I-V curve is highly reproducible until the potential across the molecule exceeds +1 V. This voltage irreversibly oxidizes the switches, and after this process, applying a negative voltage results repeatedly in a "small" current, demonstrating that the switch is open.

6.7.3 Molecular Logic

Contact persons: J.M. Tour, Rice University, and M. Reed, Yale University

Electron transport studies in molecular-scale systems have recently become possible with the utilization of advanced microfabrication and self-assembly techniques (Aviram and Ratner 1998; Petty et al. 1995). Investigations are now possible of the electronic conduction through conjugated molecules that are end-bound onto surfaces; these have been demonstrated with a scanning tunneling microscope (Bumm et al. 1996), with micromachined silicon nanopores (Zhou et al. 1997), and with proximal probes (Reed et al. 1997; Kergueris 1999). Work on the proximal probes demonstrated that 0.1 microamp of current can be transported through a single molecule (Reed et al. 1997). However, in all of the past embodiments, the electronic properties exhibit simple diodic behavior that is unsuitable for potential circuit applications. Researchers recently observed the first large and useful reversible switching behavior in an electronic device that utilizes molecules as the active component. That work is disclosed here (Chen et al. 1999).

The essential feature of the fabrication process is the employment of nanoscale device area that gives rise to a small number of self-assembled molecules (ca. 1,000), which eliminates pinhole and other defect mechanisms that hamper through-monolayer electronic transport measurements. This technique has demonstrated good control over the device area and intrinsic contact stability and produces a large number of devices with acceptable yield so that statistically significant results can be produced (Figure 6.5).

[This figure not available online until May 2000; please see printed report or CD-ROM version.]

Figure 6.5. Schematics of device fabrication: (a) cross section of a silicon wafer with a nanopore etched through a suspended silicon nitride membrane; (b) Au-SAM-Au junction in the pore area; (c) blowup of the active SAM region with compound **1c** sandwiched in the junction; (d) SEM micrograph of pyramid Si structure after unisotropic Si etching, i.e., the bottom view of (a); (e) SEM micrograph of etched nanopore through silicon nitride membrane (reprinted with permission from Chen et al. 1999, ©1999 American Association for the Advancement of Science).

The active electronic component (synthesis shown in Figure 6.6) was made from an organic compound upon exposure to Au. Figure 6.7 illustrates the I-V characteristics of the Au-(**1c**)-Au devices at 60 K. The I-V is fully reversible upon change in bias sweep direction. This is the first observation of robust and large negative differential resistance (NDR) in a device where molecules form the active region with peak-to-valley-ratios (PVRs); and the PVRs here are >1000:1. The performance exceeds that observed in typical solid state quantum well resonant tunneling heterostructures. Therefore, in addition to the obvious size advantages for scaling, the intrinsic device characteristics (i.e., valley current shutoff) may be superior to solid state embodiments; present silicon devices rarely exceed PVRs of 100:1.

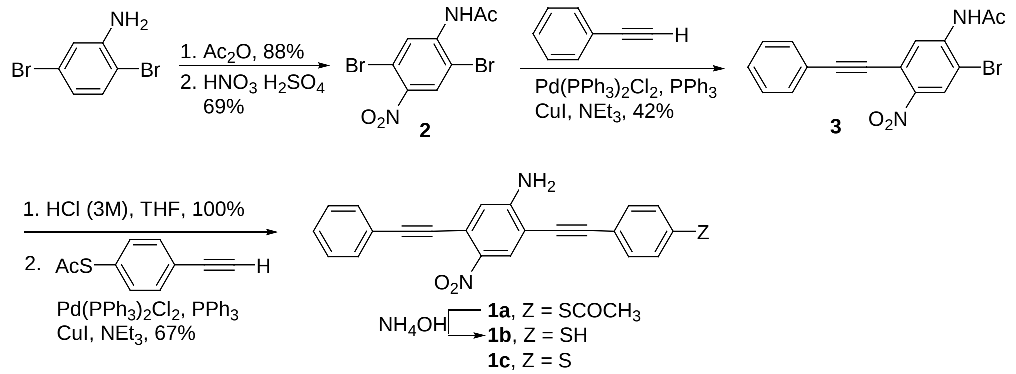

Figure 6.6. Schematic of the synthesis of the active molecular compound and its precursors (**1a-c**).

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Figure 6.7. I-V characteristics of the Au-(2'-amino-4-ethynylphenyl-4'-ethynylphenyl-5'-nitro-1-benzenethiolate)-Au devices at 60 K. The peak current density is ~50 A/cm^2, the NDR is ~ -400 $\mu\Omega$-cm^2, and the PVR is 1030:1 (reprinted with permission from Chen et al. 1999, ©1999 American Association for the Advancement of Science).

6.7.4 A Field-Effect Transistor Made from a Single-Wall Carbon Nanotube

Contact person: P. Avouris, IBM Research

Several research groups around the world have succeeded in fabricating electrical switches such as the field-effect transistor from single-walled carbon nanotubes. In the case illustrated in Figure 6.8, a single-walled carbon nanotube 1.6 nm in diameter was manipulated into place using an atomic force microscope. Once placed on the metal contacts, the semiconducting tube behaved like the channel in a field-effect transistor, turning on or off depending on the applied gate voltage. Nanotubes hold great promise as electronic elements for a variety of different nanostructures. Researchers are just beginning to understand how they conduct electricity and how to place them into appropriate device structures. It is interesting to note that both the atomic force microscope used to fabricate this structure and the carbon nanotubes that form the critical element were developed only in the past decade (Martel et al. 1998).

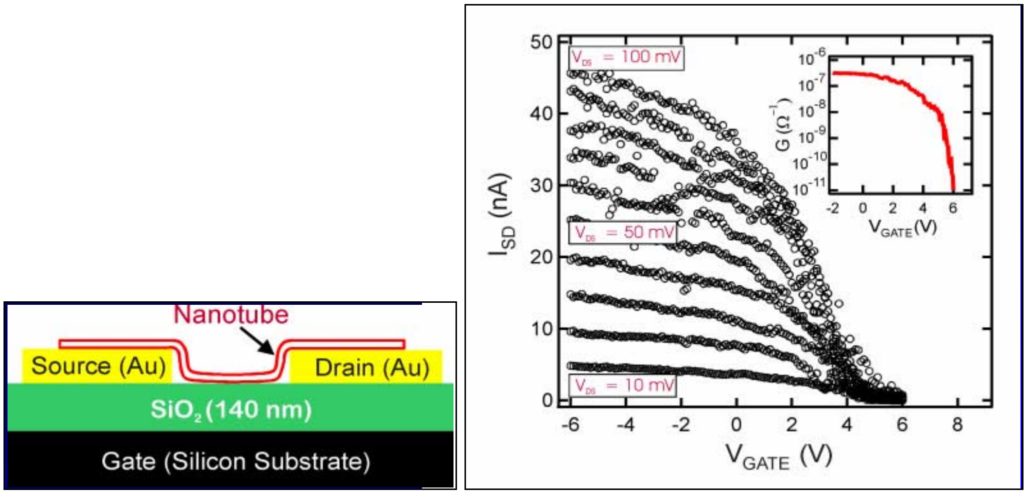

Figure 6.8. Field-effect transistor based on a single 1.6 nm diameter carbon nanotube (adapted from Martel et al. 1998, reprinted by permission; ©1998 American Institute of Physics).

6.7.5 A Commercial IBM Giant Magnetoresistance Read Head

Contact person: E. Grochowski, IBM

When certain kinds of materials systems are exposed to a magnetic field, their electrical resistance changes. This effect, called the magnetoresistive effect, is useful for sensing magnetic fields such as those in the magnetic bits of data stored on a computer hard drive. In 1988, the giant magnetoresistance effect was discovered in specially prepared layers of nanometer-thick magnetic and nonmagnetic films. By 1991, work at the IBM Almaden Research Center demonstrated that the GMR effect could be observed in easily made samples and that a special kind of GMR structure, a spin valve, could sense very small magnetic fields. This opened the door to the use of GMR in the read heads for magnetic disk drives. IBM first announced a commercial product based on this design in December 1997. In the spin valve GMR head shown in Figure 6.9, the copper spacer layer is about 2 nm thick, and the cobalt GMR pinned layer is about 2.5 nm thick. The thickness of these layers must be controlled with atomic precision.

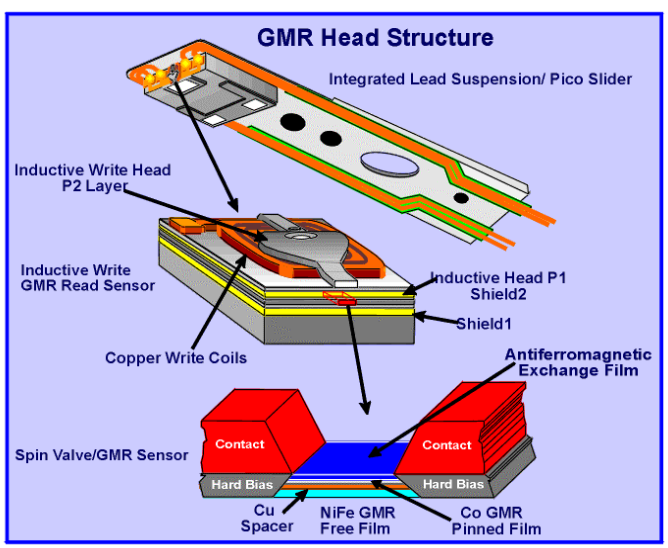

Figure 6.9. Commercial IBM giant magnetoresistance read head.

6.7.6 Nanoelectronic Devices

Contact person: G. Pomrenke, Defense Advanced Research Projects Agency (on detail from Air Force Office of Scientific Research)

Nanoelectronics offers a broad set of opportunities by focusing on quantum devices and addressing their potential for high performance through increases in density (factors of 5 to 100), speed (factors of 10 to 100), and reduced power (factors of more than 50) (see Figure 6.10). Resonant tunneling devices are being explored with demonstrated successes in multivalued logic and various logic circuits and memory circuits. SET logic and memory concepts are being explored with focus on memory applications. Molecular electronics and self-assembly approaches have shown a path towards manufacturing alternatives and device options for regimes beyond traditional scaling. Spin devices in the form of nanomagnetics using the magnetoresistive effect in magnetic multilayers have demonstrated their use for nonvolatile, radiation-hard memory. Quantum cellular automata and coupled quantum dot technology are being explored and their potential assessed for transistorless computing. By exploring Si-based heterojunctions, bandgap engineering, vertical device structures, and quantum devices, inroads are being made into extending CMOS capabilities. Potential applications are in digital radar, electronic support measures (ESM) receivers, ATM data stream processing, wide bandwidth communications, digital image processing, waveform generation, and the broad area of analog to digital (A/D) applications. Demonstrations have shown the efficacy of resonant tunneling devices in various network environments. The long-term vision for nanoelectronics sees the use of quantum devices in other high performance systems especially in telecommunications for signal processors and electronics for A/D converters in detectors.

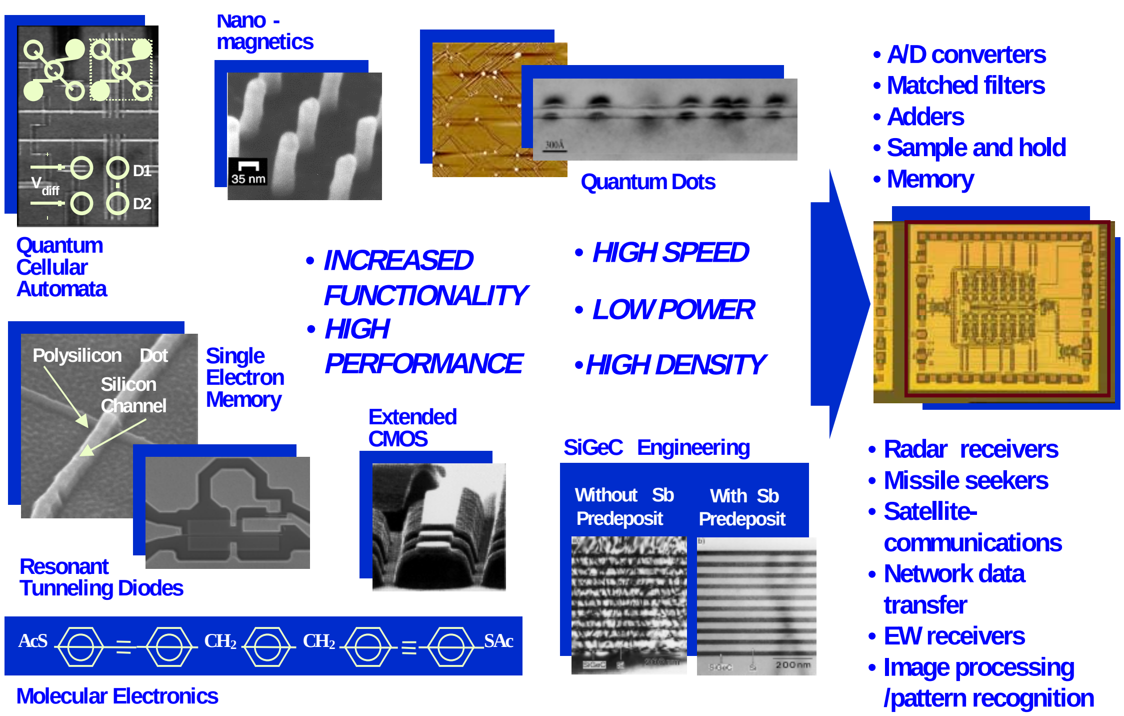

Figure 6.10. Nanoelectronics: device and architecture options for high-performance electronics.

6.7.7 Resonant Tunneling Devices in Nanoelectronics

Contact person: G. Pomrenke, Defense Advanced Research Projects Agency (on detail from Air Force Office of Scientific Research)

Resonant tunneling and other tunneling devices have had a history spanning almost three decades; however, it was not until 1997 that these devices could be seriously considered as part of functional circuits. The crucial technology for advancing these quantum devices has been epitaxial growth and process control at the nanoscale. This has meant control at the atomic layer level, resulting in flexible manufacturing, long-term process repeatability, and first-pass success. The resonant tunneling diode (RTD) consists of an emitter and collector region, and a double-tunnel barrier structure that contains a quantum well, as shown in the energy band diagrams of Figure 6.11. This quantum well is so narrow (5-10 nm) that it can only contain a single so-called “resonant” energy level.

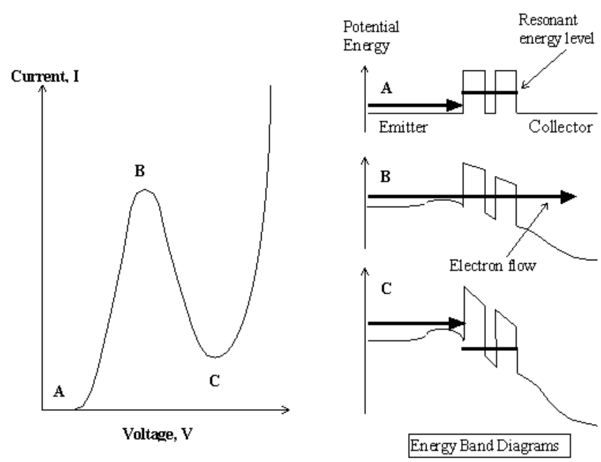

Figure 6.11. Resonant tunneling device (Moffat 1999).

The principle of this device is that electrons can travel from the emitter to the collector only if they are lined up with this resonant energy level. Initially, with a low voltage across the device (at point A), the electrons are below the point of resonance, and no current can flow through the device. As the voltage increases, the emitter region is warped upwards, and the collector region is warped downwards. Eventually, the band of electrons in the emitter line up with the resonant energy state and are free to tunnel through to the right. This gives an increase in the current up to the peak at point B. As the voltage across the device increases, the electrons are pushed up past the resonant energy level and are unable to continue tunneling. This can be observed by the drop in current to the valley at point C. As the voltage continues to increase, more and more electrons are able to flow over the top of the tunnel barriers, and the current flow rises. The current-voltage characteristic of this device is similar to that of the Esaki tunnel diode, in that it exhibits a peak and a valley in the curve. The difference is that RTDs have a much lower device capacitance, which allows them to oscillate faster, and their current-voltage characteristics (i.e., the positions of the peak and the valley) can be shaped with the appropriate bandgap engineering.

DARPA’s Ultra Electronics Program accomplished the invention and simulation of a compact adder circuit with GHz speeds using redundant digit, multivalued logic, and the world's first demonstration of an integration process for yielding the core circuit elements needed for adders (see Figure 6.12), signal processors, and multivalued logic circuits. The technology developed was subsequently transferred into circuit development efforts, which have led to the demonstration of a 4 bit 2 GHz analog-to-digital converter, 3 GHz (40 dB spur-free dynamic range) clocked quantizer, 3 GHz sample and hold (55 dB linearity), clock circuits, shift registers, and ultralow power SRAM (50 nW/bit) (Seabaugh 1998). The "invention" of functional devices based on quantum confinement occurred in the early 1980s. In the optoelectronic area a good example is the self-electro-optic effect device (SEED), based on the quantum-confined Stark effect, for photonic switching applications. Another example is the vertical cavity surface-emitting laser (VCSEL), the backbone of optical communications. The technology offers two-fold speed increases, almost 10 times lower component counts, and 10 to 2,000 times lower power over conventional devices.

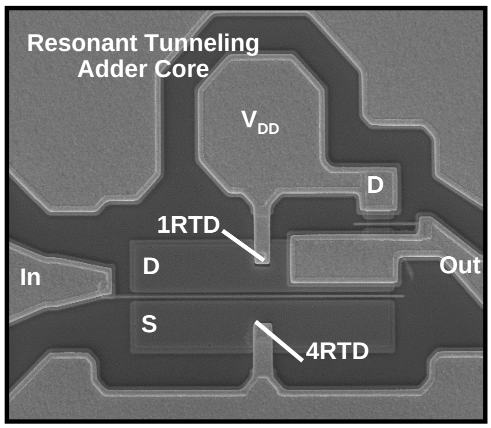

Figure 6.12. Resonant tunneling adder core (Seabaugh 1998).

6.7.8 Nanodevices and Breakthroughs in Space Exploration

Contact person: N.B. Toomarian, Jet Propulsion Laboratory

After more than three decades of exploring space, the National Aeronautics and Space Administration (NASA) has completed an initial reconnaissance of our solar system. The next missions will involve sending spacecraft to destinations that are much more difficult to travel to, like the Sun or Pluto. Also, spacecraft will be required to perform more difficult tasks, such as landing on a celestial body, collecting a sample of its material, and returning it to Earth. To carry out such technically challenging missions at an affordable cost, NASA has created the Deep Space Systems Technology Program, known as X2000. Every two to three years starting in the year 2000, the program will develop and deliver advanced spacecraft systems and body structures to missions bound for different areas of the solar system and beyond. In order to achieve reduction in the size of spacecraft, the avionics systems of the spacecraft are being reduced in size with each delivery of X2000, in part by means of integrating nanotechnology with microtechnology. Figure 6.13 attempts to chart the forecasts of the mass, volume, and power of future avionics systems of spacecraft. The leftmost column shows the Mars Pathfinder spacecraft, which represents the current state of the art.

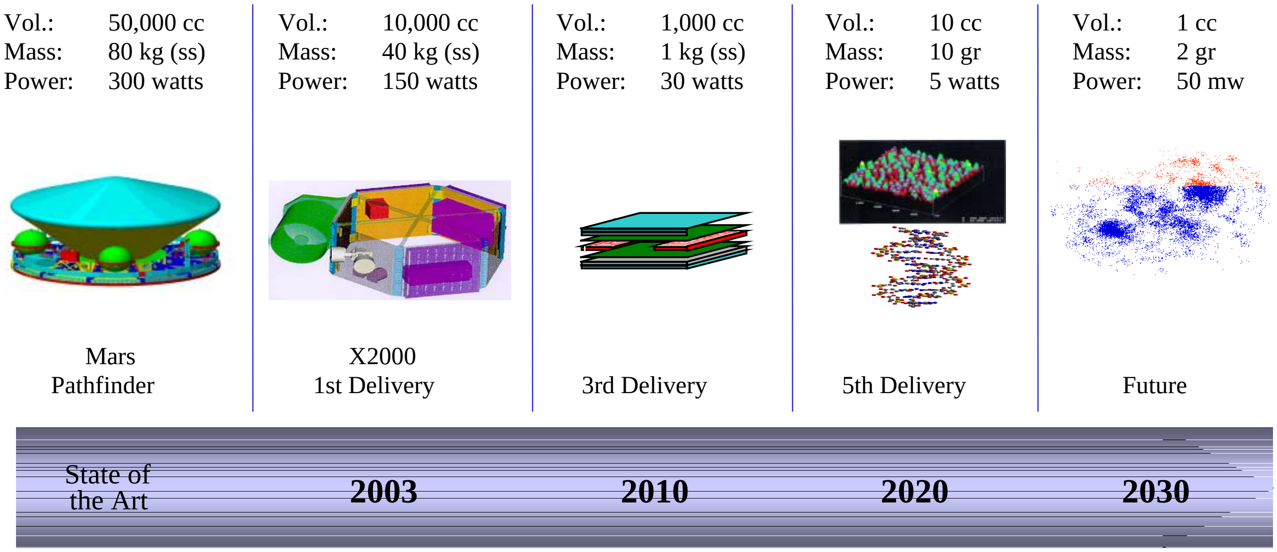

Figure 6.13. Avionics roadmap.

The first delivery for X2000 is an integrated avionics system that subsumes the functionalities of command and data handling, attitude control, power management and distribution, and science payload interface. Advanced packaging technologies as well as advanced design automation techniques are used to define a highly integrated, modular, building-block architecture for highly reliable and long-term survivable deep-space planetary missions. Advanced low-power techniques and architectures will drastically reduce overall power consumption compared to currently available flight hardware.

"System On A Chip" (SOAC) will prototype single-chip and multichip module solutions that lead towards an avionics system on a chip. This chip will integrate the avionics system that is being developed for the X2000 avionics deliverable. That is, the chip will include power management, sensor technology, and telecommunications modules, together with CPU and storage technology. To accomplish this, nanotechnology will be needed to miniaturize and integrate the different subsystems.

The goal for the year 2020 is to establish and maintain a world-class program to research revolutionary computing technologies (RCT) that will not only take us beyond the limits of semiconductor technology scaling but also will enable the vision of a "thinking spacecraft." A thinking spacecraft would be a totally autonomous, highly integrated, extremely capable spacecraft that operates at ultralow power. To achieve this goal, without a doubt, we need to employ nanoscience. In spite of the phenomenal advances in digital computing in recent years and those expected in the near future, even future supercomputers cannot compete with biological systems in performing certain ill-defined tasks such as pattern recognition, sensor fusion, fault-tolerant control, and adaptation to the environment. Biological systems address these types of problems with extreme ease and very low power. The forth column from the left in Figure 6.10 (Fifth Delivery) depicts two different technologies based on nanoscience that may have a great impact on the capabilities of our spacecraft by the year 2020:

- *Quantum computing*, that is, a joint venture between computer science and quantum physics. Although, the concept of a quantum computer is simple, its realization is not. Two issues motivate quantum computing:
  - Quantum mechanical concepts must be applied to solve intractable (NP-complete) computing problems.
  - From a computer miniaturization point of view, the size limit of a bit of information is important. Recently, this issue has attracted increased attention, due to the current development of nanotechnology and the design problems of semiconductor and metal devices that are approaching the quantum size limit. Consequently, the idea of quantum computing, in which the elements that carry the information are atoms, has attracted the attention of many scientists.

- *Biomimetics*, that is, systems or technologies inspired by architectures, functions, mechanisms, and principles found in biological systems, for example:
  - One gram of DNA could possibly store all the data in the Library of Congress.
  - The human brain contains about 10^{14} interconnects and operates at 10^{16} operations per second, using ultra low power and imprecise computing elements.
  - Humans are endowed with an immune system that provides recovery from illness—a "self-repair system."

As devices become smaller, lighter, and consume less power, NASA will be able to design and fly space probes on missions that are not currently possible.

6.7.9 A Biological Nanodevice for Drug Delivery

Contact person: S. Lee, Monsanto Corporation

The nanobiological anticancer agent PK1 (Figure 6.14) exploits the enhanced permeability and retention (EPR) effect associated with disease tissues with low integrity vasculature in order to deliver cytotoxin (doxorubicin) to tumors. The synthetic backbone of PKI (N-2-(hydroxypropyl) methacrylimide or HPMA) gives the complex a size (diameter in the mid-nanometer range) that makes it unable to extravasate efficiently into healthy tissues with normal vasculature. Tumor vasculature is abnormally permeable, allowing preferential accumulation of PK1 in tumor tissue. HPMA-bound doxorubicin is non-toxic, limiting toxicity to healthy tissue, and active doxorubicin is released from the complex preferentially in tumor tissues. The labile peptidic linker tethering doxorubicin to HPMA was selected because it is the substrate for a protease known to be over-expressed in the target tumor types. PK1 increases the tolerated doxorubicin dose by more than an order of magnitude by virtue of EPR-based targeting and its engineered tumor-preferred doxorubicin release properties. It is in human clinical trial in Europe. Contemplated embellishments to this and similar polymer therapeutics include use of monodisperse nanopolymers (dendritic polymers) to enhance control of EPR properties, incorporation of protein docking domains that recognize tumor associated antigens to tether the complex following its delivery to the tumor, and incorporation of additional antitumor agents thought to have synergistic effects with cytotoxins, that is, angiostatic agents, among others (Duncan 1997).

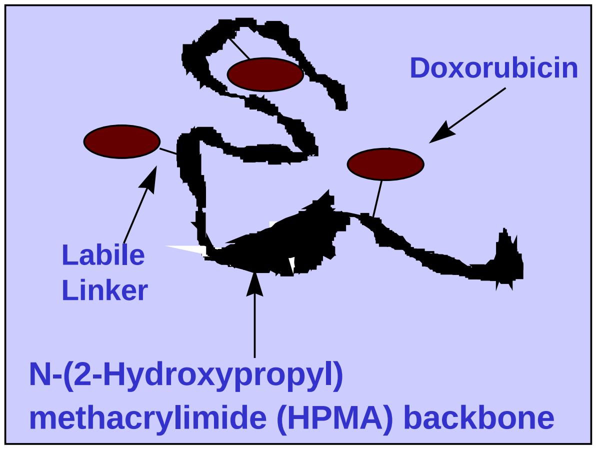

Figure 6.14. The nanobiological anticancer agent PK1 (Lee 1998).

6.7.10 Nanotechnology on a Chip: A New Paradigm for Total Chemical Analysis Systems

Contact person: T.A. Michalske, Sandia National Laboratories

The ability to make chemical and biological information much cheaper and easier to obtain is expected to fundamentally change healthcare, food safety, law enforcement, national security, and many other areas of direct interest to the American public. The vision of broadly available chemical analysis is fueling an international effort to develop "μChemLab™-on-a-chip" technology. Micro-total analysis systems (μ-TAS, as they are often referred to) are distinguished from simple sensors because they conduct a complete analysis; a raw mixture of chemicals goes in and an answer comes out. Sandia National Laboratories is developing a hand-held μChemLab™ demonstrator that will analyze for air-born chemical warfare agents and liquid-based explosives agents. The μChemLab™ development project brings together an interdisciplinary team of about 50 staff members from throughout the laboratory in areas of expertise including microfabrication, chemical sensing, microfluidics, and information sciences. Although nanotechnology plays an important role in current μTAS efforts, most μTAS approaches use miniaturized versions of conventional architecture and components to achieve system tasks. Small valves, pipes, pumps, separation columns, etc. are patterned after their macroscopic counterparts. Even though we are finding that these miniaturized components can work as well as (and sometimes better than) their macroscopic analogs, they simply will not allow for the vision of chemical laboratories in a grain of sand.

Nanotechnology will enable a completely new architecture, or nano-TAS. The ability to build materials with switchable molecular functions could provide completely new approaches to valves, pumps, chemical separations, and detection. For example, fluid streams could be directed by controlling surface energy without the need for a predetermined architecture of physical channels. Switchable molecular membranes and the like could replace mechanical valves. By eliminating the need for complex fluidic networks and micro-scale components used in current μ-TAS efforts, nano-TAS is a fundamentally new approach to allow greater function in much smaller, lower power total chemical analysis systems.

6.7.11 The Development of Useful Nanotech Robotic Systems

Contact person: M.W. Tilden and T.C. Lowe, Los Alamos National Laboratory

It is potentially feasible to manufacture nano-robots that are capable of sophisticated symmetric behaviors, either through independent function or by assembling themselves into collective units. Imagine, for example, high-resolution video screens that can repair themselves simply by having a microscopic robot at each screen element. These "pixelbots" would be capable of producing light, but also be smart enough to remove themselves from the video array should they ever fail. Other pixelbots would sense the vacancy left by any defective device and reorganize themselves to fill the hole. Another example is the incorporation of autonomous "nurse" robots into the human body that are chemically benign but are capable enough to remove cancer cells at the source. Having the ability to discriminate between healthy and cancerous cells, the "nurse-bots" would function independently to continuously heal tissue in ways beyond the current ability of the human body. The same notion can be implemented in self-optimizing silicon memories or processors, where a blown transistor would mean one just had to wait for the computer to heal itself.

One key to establishing such capabilities is research into autonomous self-assembled systems. Researchers at Los Alamos National Laboratory are exploring these systems by creating very inexpensive macro-scale robots. These sense and adapt to their environment, including assimilating other robots to execute such tasks as searching for and marking the location of unexploded land mines (Figure 6.15). The capabilities of these intelligent cellular systems are readily scaled, providing untapped possibilities for large numbers of inexpensive nano-machines to become microscopic building blocks for heretofore unimaginable functions—a form of "nano-Lego" for the new millennium with novel, untapped market potential.

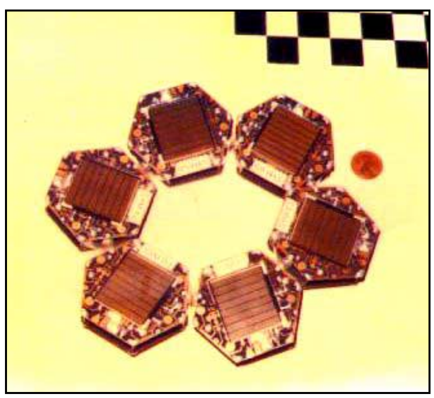

Figure 6.15. Models for nanoscale: Three-inch-diameter self-assembled robots mark the spot where an unexploded mine rests under the surface. Such robots are cheap, solar-powered, and have no processor to make application or miniaturization difficult.

6.7.12 Integrated Nanotechnology in Microsystems

Contact person: S.T. Picraux, Sandia National Laboratories

Advances in nanotechnology will have a profound effect on the future of integrated microsystems. The integration of microelectronic, microelectromechanical, optical, and chemical microsensors into "systems on a chip" is an area that may involve mechanical, optical, and/or chemical functions as well. As illustrated in Figure 6.16, these advances will make possible miniaturized systems that sense, think, talk (communicate), and act. However, these microscale systems will only become a reality if enabled by the control of performance at the nanoscale. Thus, for example, advances in micro-electromechanical systems (MEMS) and photonics shown in the figure depend on discoveries in nanoscience and nanoscale fabrication.

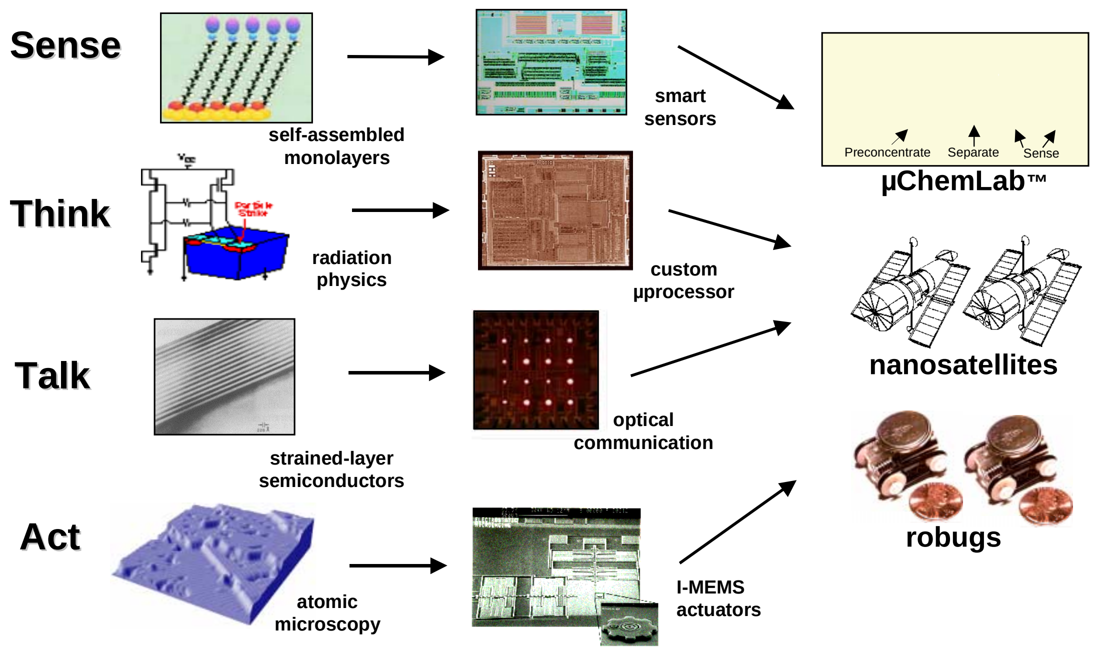

Figure 6.16. The control of mechanical, electrical, optical, and chemical properties at the nanoscale will enable significant improvements in integrated microsystems.

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